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### **Microgravity Acceleration Environment of the International Space Station (Panel)**

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## MICROGRAVITY ACCELERATION ENVIRONMENT OF THE INTERNATIONAL SPACE STATION (PANEL)

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### ABSTRACT

This paper examines the microgravity environment provided to the early science experiments by the International Space Station vehicle which is under construction. The microgravity environment will be compared with predicted levels for this stage of assembly. Included are initial analyses of the environment and preliminary identification of some sources of accelerations. Features of the operations of the accelerometer instruments, the data processing system, and data dissemination to users are also described.

### ACRONYMS & ABBREVIATIONS

ADVASC	ADVANCED ASTROCULTURE™
AOS	Acquisition of Signal
ARIS-ICE	Active Rack Isolation System - ISS Characterization Experiment
EXPRESS	EXpedite the PROcessing of Experiments to the Space Station
FGB	Functional Cargo Block (Russian acronym)
$g_0$	Earth's gravity level (nominally $9.81 \text{ m/s}^2$ )
GMT	Greenwich Mean Time
GRC	NASA Glenn Research Center
HiRAP	High Resolution Accelerometer Package
ISS	International Space Station
LOS	Loss of Signal
MAMS	Microgravity Acceleration Measurement System
MCOR	Medium-rate Communication Outage Recorder
mg	$10^{-3}$ times nominal Earth's gravity level ( $g_0$ )
NASA	National Aeronautics and Space Administration

OSS	OARE Sensor Subsystem
PIMS	Principal Investigator Microgravity Services
PCS	Physics of Colloids in Space
PSD	power spectral density
RMS	root-mean-square
SAMS	Space Acceleration Measurement System
STS	Space Transportation System
$\mu g$	$10^{-6}$ times nominal Earth's gravity level ( $g_0$ )

### INTRODUCTION

The investigation of physical sciences in microgravity conditions has been actively pursued by National Aeronautics and Space Administration (NASA) beginning with Skylab, continuing through a series of payloads on Shuttle missions for over fifteen years, and long-term research through a cooperative program on the Mir space station. Physical science research made a new beginning in early 2001 when experiments were installed and began operating on the International Space Station (ISS). Early scientific investigations will be operated on the ISS even though the ISS will not be completed for several more years.

In step with these investigations has been the measurement of parameters important to the science, such as combustion by-products, fluid visualization, sensitive temperature measurements, and the microgravity (acceleration) environment itself. For most experiments, the acceleration environment cannot be ignored. Ideally, the acceleration level would be zero on a microgravity platform, but in reality, accelerations exist due to a variety of sources, such as pumps, fans and vehicle motions. Such accelerations may adversely affect experiments by causing effects such as convection, sedimentation, or mixing of experimental samples. The measurement and understanding of this acceleration environment is a necessary aspect of conducting physical science research in microgravity conditions.

A primary mission of the International Space Station Program (ISSP) is to provide a premier microgravity laboratory environment for fluids, combustion, materials, biotechnology, fundamental physics, and life science research. After the ISS assembly is complete there will be planned intervals in which the vehicle will be in a Microgravity Mode of operation during which time the microgravity environment will be maintained according to ISS Program requirements. Before that time, though, during the assembly phase, the ISS Program is not constraining the vehicle, operations, nor the crew to observe a Microgravity Mode of operation. The early science investigations will need to endure the environment presented during the assembly phase.

A NASA Space Acceleration Measurement System (SAMS) instrument was among the first U.S. microgravity experiments installed and operated on the Mir space station during the NASA-Mir Science Program. This instrument characterized the acceleration environment in which the later U.S. experiments would be operated. In addition, being an identical instrument as those flown on the Shuttle missions, the data provided an apples-to-apples comparison of the Mir environment relative to the Shuttle environment. In a similar vein, acceleration measurements are being made early on the ISS to characterize the environment for the science investigations yet to come.

The SAMS and the Microgravity Acceleration Measurement System (MAMS) projects at NASA Glenn Research Center (GRC) provide acceleration measurement systems as well as operational support of these systems to the ISS Program. The Principal Investigator Microgravity Services (PIMS) project provides analysis, interpretation, and dissemination of the data and information gleaned from the acceleration data and ISS operations.

The Microgravity Integrated Performance Team (MIPT) (formerly the Microgravity Analysis & Integration Team) serves as the focal point for all ISS microgravity activities that effect the system level microgravity performance of the ISS. The MIPT is charged with the task of ensuring that the ISS Program (ISSP) facilitate world class microgravity research in compliance with the microgravity performance specifications.<sup>1</sup>

This paper examines the microgravity environment provided to the early science experiments by the ISS vehicle which is under construction. The microgravity environment will be compared with predicted levels for this stage of assembly. Included are initial analyses of the environment and preliminary identification of some sources of accelerations. Features of the operations of the

accelerometer instruments, the data processing system, and data dissemination to users are also described.

### **ISS PROGRAM REQUIREMENTS**

The top-level documents for the ISS Program specify that the ISS will provide a microgravity environment suitable for physical science research for at least 180 days each year. These requirements are contained in the System Specification for the International Space Station<sup>2</sup> and are summarized in Figure 1. These requirements are grouped in four main categories, duration, vibratory, quasi-steady, and transient. Each of these areas was a consideration during the design, construction, analysis, and test of the ISS vehicle and development of the operational methodologies.

These microgravity requirements are not currently imposed on the ISS because the vehicle is still under construction. At the time that the assembly phase is complete, these requirements will be imposed on the ISS operations in order that a satisfactory microgravity environment is presented to the on-board research facilities.

The control of the microgravity environment via the design, development, test, verification, and operational aspects of the ISS will be managed by the MIPT.<sup>3</sup> Its principal task is to assure the effective implementation of the microgravity requirements defined in System Specification for the ISS<sup>2</sup>. Those specifications specify the minimum duration of the microgravity mode and the associated permissible accelerations limits at the internal user payload locations.

### **INSTRUMENTS**

Many of the early microgravity science experiments on the Shuttle incorporated an accelerometer in the experiment development cost and schedule. After those initial experiments, NASA realized that a more effective method of measuring the microgravity acceleration environment was for a general purpose family of accelerometer instruments to support multiple experiments on multiple missions. The solution was the SAMS units which were flown on over twenty Shuttle flights supporting payloads in the Shuttle middeck, Spacelab module, Shuttle cargo bay, and SPACEHAB module. A SAMS unit was also installed on Russia's Mir space station for the extent of the NASA-Mir Science Program.

### **Second Generation SAMS**

The second-generation SAMS for ISS is a general purpose instrument with remote sensor heads for acceleration measurement at or near experiment sample chambers and other locations of interest. During ISS

Increment 2, the SAMS Interim Control Unit (ICU) was located in the EXPedite the PROcessing of Experiments to the Space Station (EXPRESS) Rack 2 with five sensor heads at various locations in EXPRESS Racks 1 and 2 as listed in Table 2. The SAMS ICU is the control computer for the total SAMS system with all SAMS acceleration data and housekeeping data routed through the ICU for downlink. The low-pass cut-off frequency of the SAMS sensor heads is variable from 25 to 300 Hz for vibratory measurements from 0.01 Hz to the cut-off frequency.

SAMS success criteria for Increment 2 was focused on support for the primary customers of SAMS which were the Active Rack Isolation System ISS Characterization Experiment (ARIS-ICE) and Physics of Colloids in Space (PCS). ARIS-ICE required three functional sensor heads and PCS required one functional sensor head. This success criteria has been met for operations to date.

### **MAMS**

The MAMS instrument is comprised of two major components, the OARE Sensor Subsystem (OSS) for quasi-steady measurements (at frequencies below 0.01 Hz) and the High Resolution Accelerometer Package (HiRAP) for vibratory measurements from 0.01 to 100 Hz. Both of these three-axis sensors are located in the MAMS enclosure which was installed in EXPRESS Rack 1 during ISS Increment 2.

## **ISS OPERATIONS**

### **Acceleration Measurement System Activations**

The MAMS is located within EXPRESS rack 1, which for Increments 2 and 3 is a continuously powered EXPRESS rack. Consequently, MAMS was first activated on May 3, 2001 at Greenwich Mean Time (GMT) 123/13:58:24. As with any MAMS activation, the power-on activation initiates data flow from the MAMS OSS sensor only and the HiRAP sensor must be commanded on separately. The initial HiRAP activation was performed on May 11, 2001 at GMT 131/01:24:08. Following their initial checkout and verification, both instruments have been active for nearly all of Increments 2 and 3.

The activation of EXPRESS rack 2 was delayed significantly after the departure of Shuttle flight 6A from the ISS. Consequently, the SAMS ICU was not activated until June 4, 2001. The first acceleration data were received on June 4, 2001 at GMT 155/22:09. Sequential activation of the sensors in EXPRESS rack 1 was further delayed so the first acceleration data from these sensors were received beginning on June 19, 2001 and the last RTS was activated on June 22, 2001.

### **PIMS Operations at the GRC Telescience Support Center**

The PIMS project is responsible for receiving, processing, and archiving the acceleration data from both SAMS and MAMS instruments. For both SAMS and MAMS, the acceleration data are transmitted to the ground as data packets that are routed through the ISS data network. PIMS ground support equipment located at the GRC Telescience Support Center writes each received packet into a database table dedicated to each instrument's triaxial sensor supported by PIMS. Therefore, a separate database table exists for MAMS OSS, MAMS HiRAP, and each of the five SAMS triaxial sensors.

Communication from the ISS is not continuous resulting in Acquisition of Signal (AOS) intervals and Loss of Signal (LOS) intervals. Both SAMS and MAMS acceleration data must rely on ISS on-board storage capabilities to eventually obtain acceleration data acquired during LOS intervals. This ISS on-board storage capability is provided by the Medium-rate Communication Outage Recorder (MCOR). Under normal circumstances, both SAMS and MAMS will measure and transmit acceleration data continuously throughout a given increment. Consequently, real time acceleration data are available on the ground during AOS periods and acceleration data are stored on the MCOR during LOS periods for eventual downlink during a future AOS period.

When acceleration data are transmitted to the ground, whether real time data downlink or data transmitted from a dump of the MCOR memory, the resultant acceleration data packets are stored in the PIMS database tables. The primary function of the database tables is to automatically merge AOS and LOS data packets for each sensor. Since overlaps exists between the received AOS and LOS acceleration data packets, each sensor's dedicated database table discards any redundant data packets, resulting in a table containing a contiguous set of acceleration data packets. Data are accessed from the database table to serve two separate purposes. The first purpose involves obtaining the most recent acceleration data from the table to generate real time plots of the acceleration data in a variety of plot formats supported by PIMS. These real time plots are updated during AOS intervals and electronic snapshots of the data are routed to the PIMS ISS web page<sup>4</sup>.

The second purpose involves obtaining the oldest acceleration data from the "bottom" of the table. These acceleration data are used to generate the PIMS acceleration data archives used by the PIMS data analysts to generate the plots described in this report. Since the data are processed from the "bottom" of the

table, MCOR dumps will have had time to be downlinked, received, and merged by the database table. PIMS currently waits 24 hours before generating any acceleration data archives. Like the electronic snapshots of the real time acceleration data plots, the acceleration data archives are available for download via the PIMS ISS web page.

### **MICROGRAVITY ENVIRONMENT CHARACTERIZATION**

One of the primary functions of PIMS is to analyze the acceleration data, correlate features of the acceleration environment to sources, and relate these findings to the microgravity science community, especially principal investigators.

#### **Quasi-steady regime**

The quasi-steady regime is comprised of accelerations with frequency content below 0.01 Hz and magnitudes expected to be on the order of 5  $\mu$ g or less. These low-frequency accelerations are associated with phenomena related to the orbital rate (e.g. aerodynamic drag, gravity gradient and rotational accelerations) and sources of nearly steady forces in this frequency regime (e.g. long-term venting of air or water from the ISS).

The different quasi-steady environment characteristics seen on the ISS for Increment 2 were primarily related to altitude and attitude of the station. Variation in atmospheric density with time and altitude contribute to the differences in the aerodynamic drag component. Different attitudes will affect the drag component due to the variation of the frontal cross-sectional area of the station with respect to the velocity vector.

Quasi-steady-disturbances-were-also-observed-during-a cabin air vent operation on the Shuttle in preparation for an Extra-Vehicular Activity.

**ISS flight attitude** The two primary vehicle flight attitudes flown during Increment 2 were Torque Equilibrium Attitude (TEA) and X-Axis Perpendicular to Orbital Plane (XPOP) Inertial Flight Attitude. TEA is an attitude that balances the vehicle's gravity gradient and aerodynamic drag torques. This is the attitude that will be flown during microgravity mode operations. The specific attitude (roll, pitch, and yaw) for TEA will vary with station configuration, change in mass and mass distribution, and aerodynamic properties. MAMS OSS data from a crew sleep period while the ISS was in the TEA is shown in Figure 2.

XPOP is a sun-tracking, quasi-inertial flight attitude used to maximize power generation. In the XPOP attitude, the vehicle's X axis is maintained perpendicular to the direction of flight, while the Y and Z axes are

alternately subjected to the drag vector as the vehicle completes an orbit. MAMS OSS data from a crew sleep period while the ISS was in the XPOP attitude is shown in Figure 3. Note the difference in scale values when comparing Figures 2 & 3.

**Docking and Undocking** In terms of the quasi-steady environment, the actual docking event is less of an impact than the attitude adjustments in preparation for the event. Attitude changes associated with docking and undocking activities measured by the MAMS OSS during Increment 2 were the Soyuz TM-31 undocking, Progress 4P docking, STS-104 docking, STS-105 docking, and STS 105 undocking.

**Orbiter Cabin Depressurization** In preparation for an Extra-Vehicular Activity during STS-104 docked operations, the Orbiter cabin was depressurized from 14.7 psi to 10.2 psi by venting cabin air aligned with XA. This event is evident in Figure 4 as a step in all three axes, the largest step being in the +XA direction, approximately 4 mg. A ramping back towards the original baseline due to the pressure (and thus the force) decreasing can also be seen in all three axes.

#### **Vibratory regime**

The ISS vibratory regime is comprised of accelerations between 0.01 and 300 Hz, with magnitudes that vary depending on the source of the disturbance and the relative location of the source and the measurement device. Accelerations in this regime are associated mainly with vehicle systems, experiment-related equipment, and crew activity. A summary of vibratory activity from the ISS during Increment 2 is Table 2.

**ISS Reboost** The ISS orbital altitude and the large ISS cross sectional area causes its orbit to decay due to atmospheric drag. To compensate, Shuttle thrusters and Progress engines have been used for incremental reboosts of the ISS altitude. Figure 5 is a spectrogram of SAMS SE 121f02 data showing the effects of Reboost #3 in the lower frequency range near the center of the plot.

**Air conditioner / dehumidifier** An air conditioner/dehumidifier is located in the Russian Segment Functional Cargo Block (FGB) module of the ISS and is part of the Environmental Control & Life Support System. This air conditioner (referred to by its Russian acronym SKV-1) was turned off in preparation for an Extra Vehicular Activity at around GMT 09:42:00 on 08-June-2001 as evidenced by the abrupt termination of the horizontal yellow streak in Figure 6<sup>5</sup>. This air conditioner operates at a fundamental frequency around 23.5 Hz. The spectral peak at this frequency seen in the data vanished when the air conditioner was turned off at

that time. During other operations when the air conditioner was turned on and off, the frequency varied based on its operating conditions which are unknown to the authors at the present time.

While it is unclear at this time what factors affect its operating characteristics, it is clear that this air conditioner plays a key role in the vibratory regime, albeit in a narrow range of the acceleration spectrum.

**Experiment operations** The ADVANCED ASTROCULTURE™ (ADVASC) experiment<sup>6</sup> has a number of fans, blowers, and at least two pumps among its payload equipment. Examination of acceleration data, operational timelines and communications with the ADVASC project team resulted in identification of five significant disturbances from ADVASC payload equipment. These are seen in Figure 7 where the traces end at the 53 minute mark at the time that ADVASC was powered off.

The PCS utilizes a mixer to ensure a uniform distribution of the sample cell and to eliminate sedimentation of the sample.<sup>5</sup> The initial PCS procedure involved mixing each colloidal sample for a period of approximately one hour. The color spectrogram in Figure 8 shows an example of the PCS mixer in operation with a 50% duty cycle starting on 04-June-2001, at about GMT 22:20:40.

**Crew active and quiet time** Characterization of the vehicle involves isolating signals seen in the acceleration data, investigating the characteristics of the signal, and identifying sources or possible sources of the acceleration signal. In looking at the ISS microgravity environment on a large scale, a most noticeable difference exists between the crew's sleep and awake periods on a daily basis. This effect has been seen on numerous Shuttle missions and on Mir and has been reported in various PIMS mission summary reports (see reference 7 as an example).

The ISS crew's daily routine has a normal work day between GMT 06:00 and 21:30 with their sleep time between GMT 21:30 and 06:00. There has been some time shifting of this daily routine primarily due to docking events. The difference in the environment may be seen in Figure 9 which is a comparison of acceleration spectra recorded during sleep and wake periods. During the crew sleep period, some equipment is turned off and the crew is less active with assigned tasks.

#### **COMPARISON OF ENVIRONMENT WITH ANALYTICAL PREDICTIONS**

The ISS Program has periodically developed predications of the microgravity environment for several stages of ISS assembly including the Assembly

Complete configuration. Data measured while the ISS was in the 6A configuration is compared with the analytic predication for the 6A configuration in Figure 10 for a crew sleep period and Figure 11 for a time during crew exercise on a treadmill. It should be noted that these data represent only a 100 second sample of time and the conditions of the ISS are not known for this time period.

The quasi-steady acceleration levels as measured by the MAMS and the predicted acceleration levels are compared in Figure 12. Note that the generic ISS model predicted levels are significantly higher than those predicted using a real-time model which uses actual ISS orbital parameters and solar flux data. The measured MAMS data are very close to the predicted levels from this real-time model.

#### **SUMMARY & CONCLUSIONS**

The long-awaited ISS is in orbit, initial physical science experiments are on-board being operated in a microgravity environment by the permanent crew and by ground science teams. The new age of space exploration has begun!

The microgravity acceleration levels observed so far look nearly as expected so there is an expectation that the microgravity environment at Assembly Complete should meet or at least be very close to the required levels.

#### **REFERENCES**

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[http://iss-www.jsc.nasa.gov/ss/issapt/payofc/OZ4/mgait\\_pages/mgait\\_charter.html](http://iss-www.jsc.nasa.gov/ss/issapt/payofc/OZ4/mgait_pages/mgait_charter.html)
- 2) Specification number SSP 41000R, 15 March 2000, System Specification for the International Space Station, Section 3.2.1.1.4
- 3) Microgravity Control Plan; International Space Station Program, SSP 50036B, Revision B, February 15, 1999
- 4) PIMS World Wide Web page for ISS operations  
<http://tsccrusader.grc.nasa.gov/pims>
- 5) Jules, K., Hrovat, K., and Kelly, E., ISS Increment-2 Quick Look Report: May to June 2001, NASA TM-211200, 2001
- 6) ADVASC description  
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- 7) Rogers, M. J. B.; Hrovat, K.; McPherson, K.; DeLombard, R.; and Reckart, T. A.: Summary Report of Mission Acceleration Measurements for STS-87, NASA TM-1999-208647, 1999
- 8) Jules, K., Hrovat, K., and Kelly, E., ISS Increment-2 Summary Report: May to June 2001, NASA Technical Memorandum to be published soon.
- 9) Laible, M. R., SSMRBS Runs Comparison to On-Orbit MAMS Data, MGMG #20 August 2001, NASA Conference Proceedings to be published soon.

**Table 1: SAMS and MAMS sensor locations during Increment 2**

<b>Sensor</b>	<b>Mounting location</b>
MAMS OSS	EXPRESS rack 1 in overhead bay 2 of the U.S. Laboratory Module
MAMS HiRAP	EXPRESS rack 1
SAMS 121f02	EXPRESS Rack 1
SAMS 121f03	Lower Z-panel assembly below EXPRESS rack 2 in overhead bay 1 of the U.S. Laboratory Module
SAMS 121f04	Lower Z-panel assembly below EXPRESS rack 1
SAMS 121f05	Bracket around the upper Z-panel light assembly of EXPRESS rack 2
SAMS 121f06	EXPRESS rack 2



Table 2: SUMMARY OF INCREMENT 2 VIBRATORY ANALYSIS<sup>8</sup>

Event	GMT	Sensor	Observation	Condition
Progress (4P) Docking	23-May-2001 00:24:23	MAMS HiRAP (100 Hz)	13 mg	Peak magnitude
Shuttle (7A) Docking Softmate	14-July-2001 03:08:31	MAMS HiRAP (100 Hz)	10 mg	Peak magnitude
Shuttle (7A) Docking Hardmate	14-July-2001 03:21:04	MAMS HiRAP (100 Hz)	6 mg	Peak magnitude
Shuttle (7A.1) Docking Softmate	12-August-2001 18:42:25	MAMS HiRAP (100 Hz)	29 mg	Peak magnitude
Shuttle (7A.1) Docking Hardmate	12-August-2001 19:02:35	MAMS HiRAP (100 Hz)	14 mg	Peak magnitude
SKV-1 OFF	08-August-2001 00:00 - 08:00	SAMS 121f02 (25 Hz)	less than 8 $\mu$ gRMS	$23 < f < 24$ Hz
SKV-1 ON	08-August-2001 16:00 - 23:59	SAMS 121f02 (25 Hz)	more than 37 $\mu$ gRMS	$23 < f < 24$ Hz
ADVASC OFF	02-June-2001	MAMS HiRAP (100 Hz)	0.3 mgRMS	$0 < f < 100$ Hz
ADVASC ON	02-June-2001	MAMS HiRAP (100 Hz)	1.0 mgRMS	$0 < f < 100$ Hz
PCS Sample Mix	04-June-2001	SAMS 121f06 (200 Hz)	150 mg	Peak magnitude
PCS Sample Mix	05-July-2001	SAMS 121f03 (100 Hz)	22 mg	Peak magnitude
PCS Sample Mix	05-July-2001	SAMS 121f04 (100 Hz)	10 mg	Peak magnitude
MAMS Fan OFF	30-August-2001 15:42-15:44	SAMS 121f02 (200 Hz)	31.5 $\mu$ gRMS	$182.3 < f < 183.7$ Hz
MAMS Fan ON	30-August-2001 15:45 - 15:47	SAMS 121f02 (200 Hz)	95.6 $\mu$ gRMS	$182.3 < f < 183.7$ Hz
Before TVIS	28-June-2001 09:45 - 09:46	SAMS 121f04 (100 Hz)	65.7 $\mu$ gRMS	$6 < f < 22$ Hz
During TVIS	28-June-2001 10:35 - 10:36	SAMS 121f04 (100 Hz)	502.8 $\mu$ gRMS	$6 < f < 22$ Hz
Crew Asleep	03-June-2001 08:40 - 08:44	MAMS HiRAP (100 Hz)	9 $\mu$ gRMS	$0.06 < f < 6$ Hz
Crew Awake	03-June-2001 08:48 - 08:52	MAMS HiRAP (100 Hz)	40 $\mu$ gRMS	$0.06 < f < 6$ Hz



# ISS Microgravity Environment

## THE Requirement for the International Space Station



DURATION

VIBRATORY

QUASI-STEADY

TRANSIENT

### Mode: Microgravity – habitable

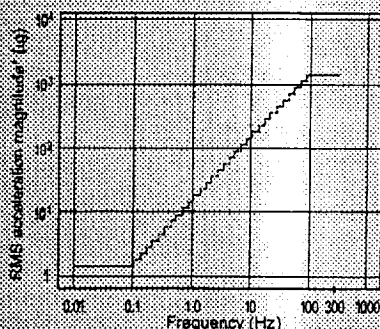
This mode consists of capabilities required for microgravity research by user payloads in a habitable environment. This mode does not include the effects of crew activity, but does include the effects of crew equipment, such as the operation of exercise devices and latched or hinged enclosures. Crew effects will be mitigated to the extent possible. This mode consists of the capabilities described in SSP 41000 and the following unique capability.

### Capability: Support microgravity experiments

The purpose of this capability is to establish the required environment for microgravity experiments. The Space Station shall provide the following microgravity acceleration performance for at least 50 percent of the internal payload locations (excluding Nadir window payload location) for 180 days per year in continuous time intervals of at least 30 days:

- a. At the centers of the internal payload locations, a quasi-steady ( $<0.01$  Hz) acceleration
  - (1) Magnitude less than or equal to 1 micro-g
  - (2) Component perpendicular to the orbital average acceleration vector less than or equal to 0.2 micro-g
- b. At the structural mounting interfaces to the internal payload locations
  - (1) A vibratory acceleration limit as defined in the figure below
  - (2) A transient acceleration limit for individual transient disturbance sources less than or equal to 1000 micro-g per axis
  - (3) An integrated transient acceleration limit for individual transient disturbance sources less than or equal to 10 micro-g seconds per axis over any 10 second interval

The Space Station shall monitor and record the microgravity environment at selected locations.



for  $0.01 \leq f \leq 0.1$  Hz:  $a \leq 1.6 \mu g$   
 for  $0.1 < f \leq 100$  Hz:  $a \leq f \times 16 \mu g$   
 for  $100 < f \leq 1000$  Hz:  $a \leq 1600 \mu g$   
 where:  $f$  = frequency  
 $a$  = acceleration

\*NOTE: Root-mean-square acceleration magnitude in  $1/3$  octave bands average over 100 seconds.

Vibroacoustic microgravity acceleration limits for the International Space Station vehicle

<http://www.grc.nasa.gov/WWW/MMAP/index.html>

Figure 1: ISS microgravity requirements

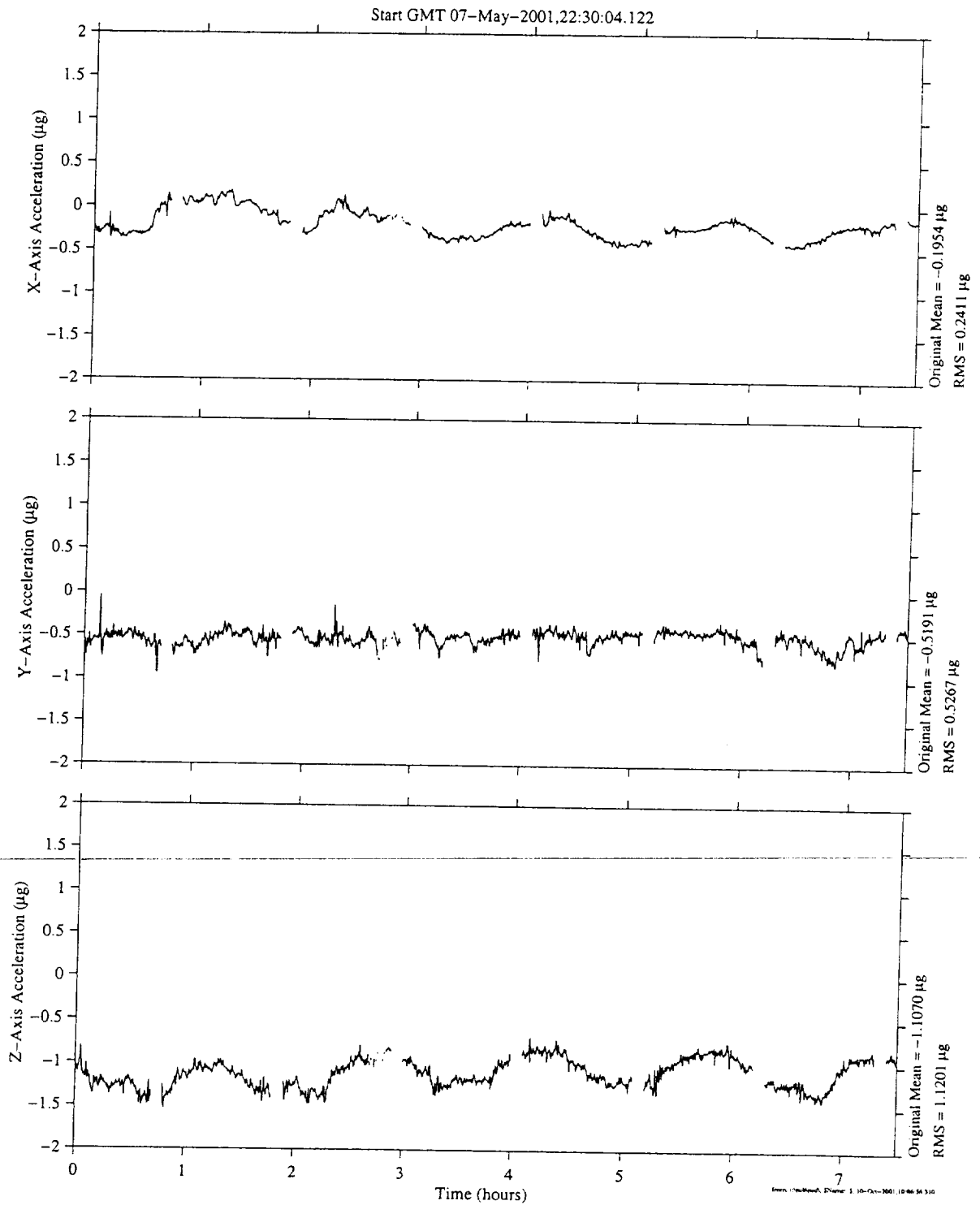


Figure 2: Microgravity environment with ISS in Torque Equilibrium Attitude (Crew Sleep Period)

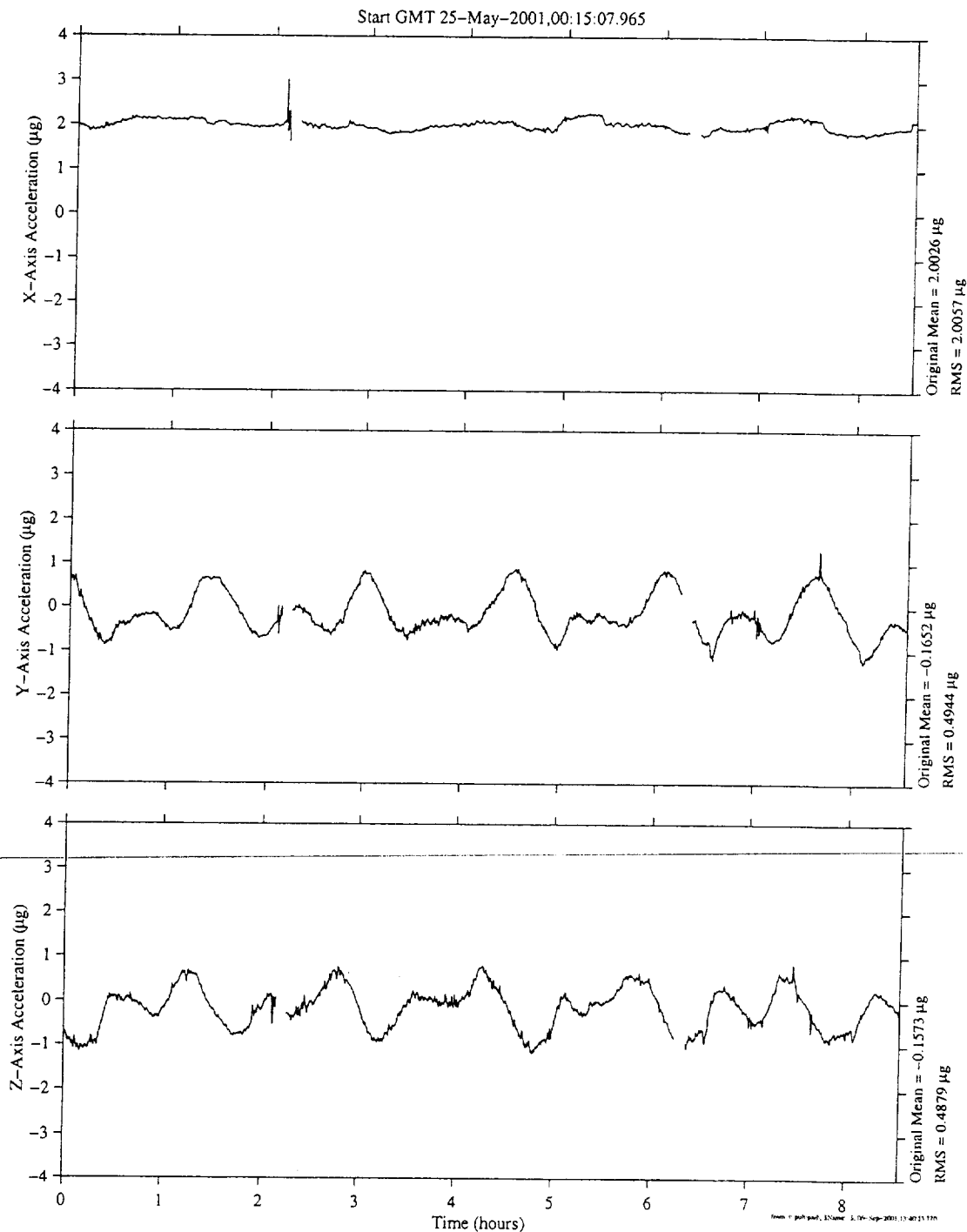


Figure 3: Microgravity environment with ISS in XPOP Attitude (Crew Sleep Period)

# 10.2 Orbiter Cabin Depressurization During STS-104

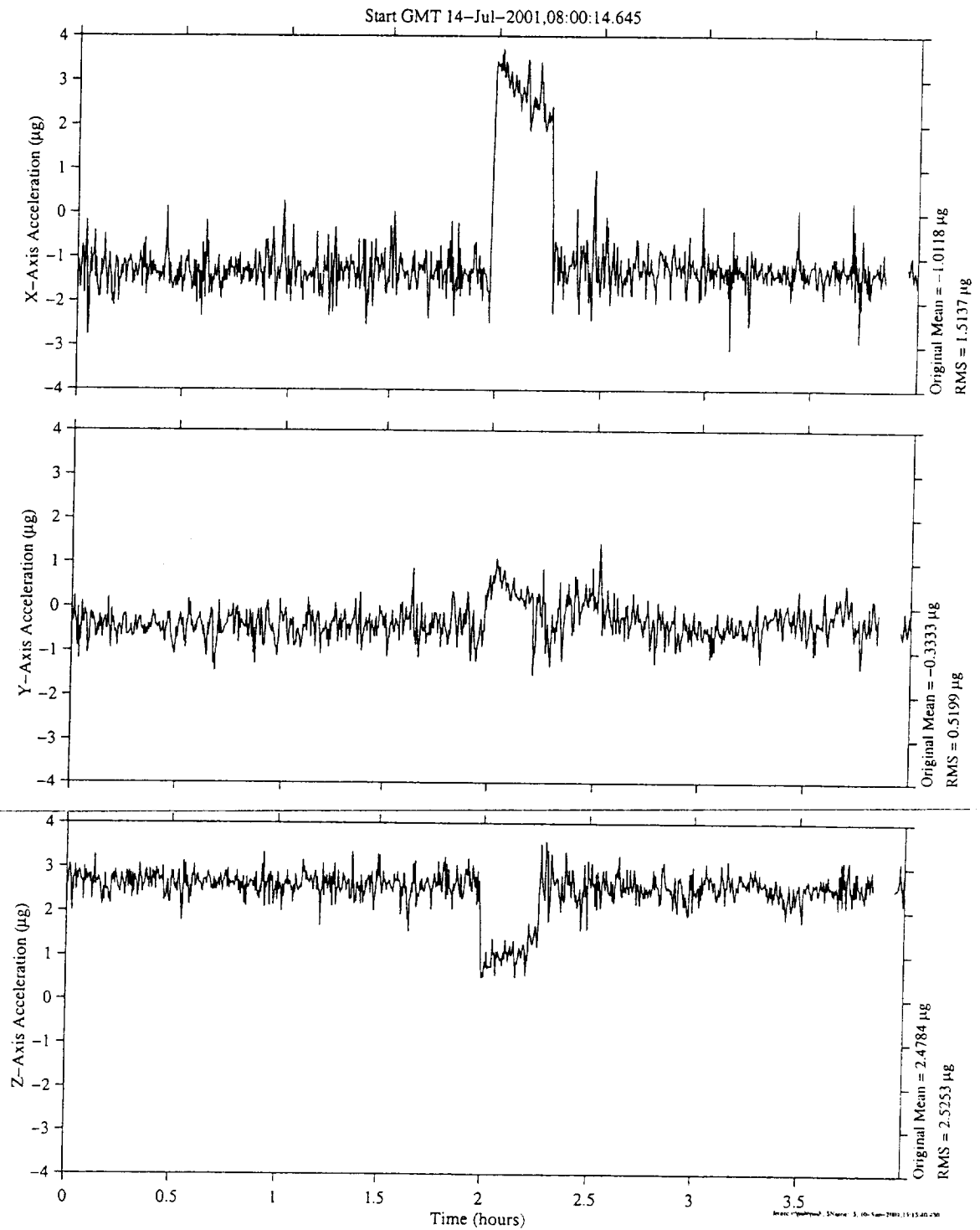


Figure 4: Orbiter cabin depressurization

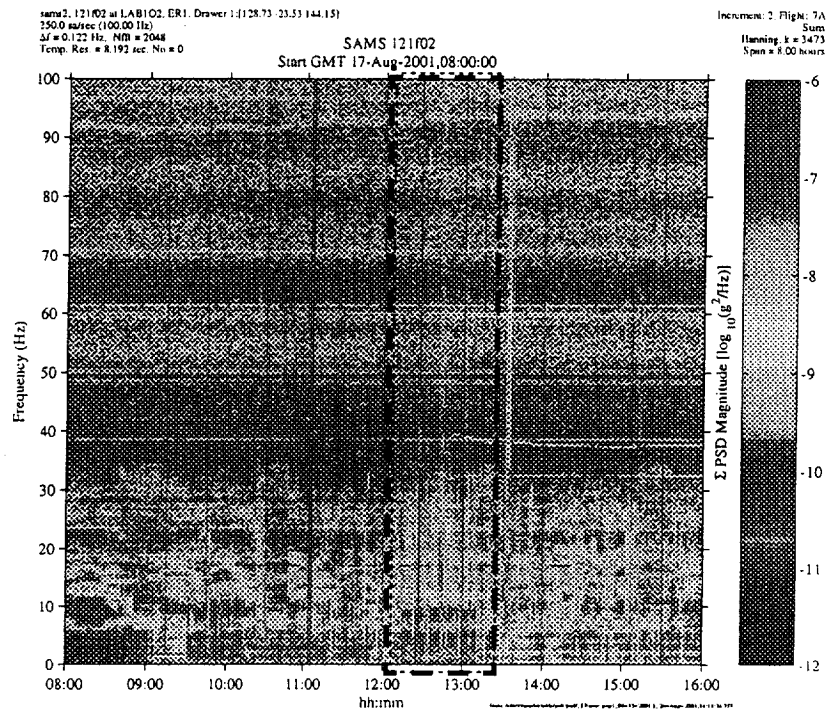


Figure 5: Effect of ISS reboost operation

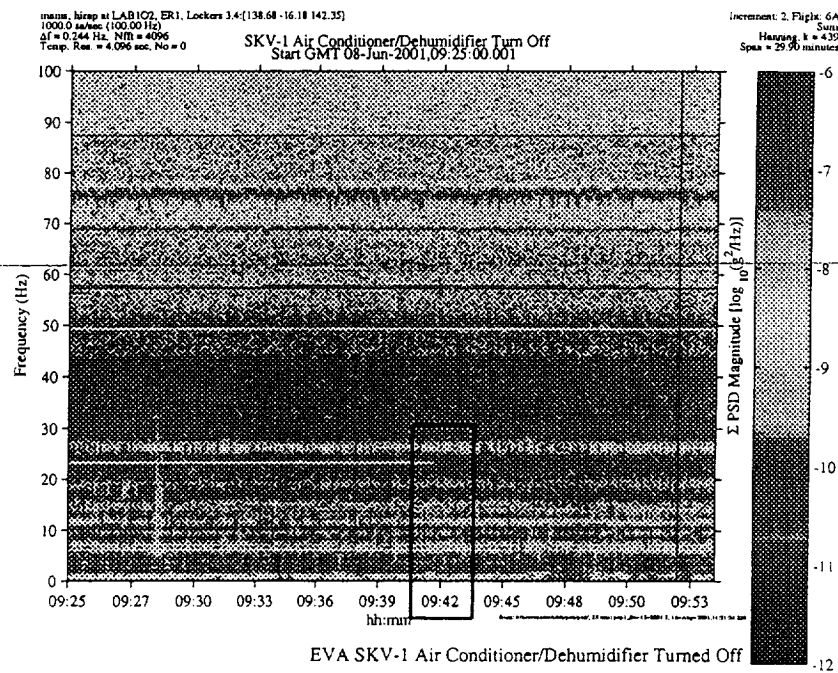


Figure 6: SKV-1 air conditioner tuned off in preparation for an ISS Extra Vehicular Activity

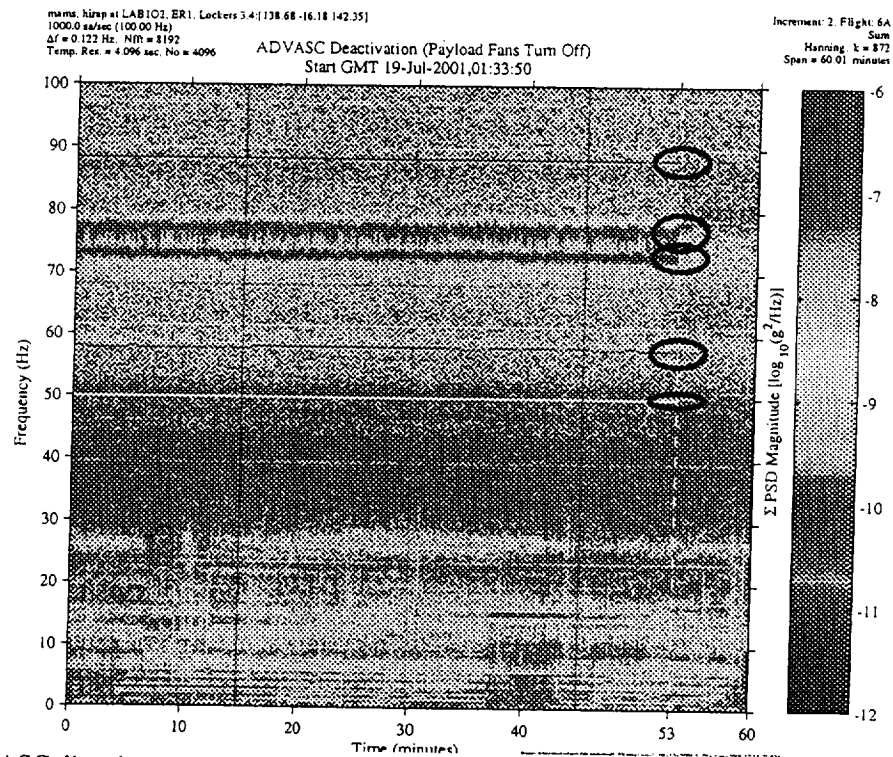


Figure 7: ADVASC disturbances ending when ADVASC was deactivated

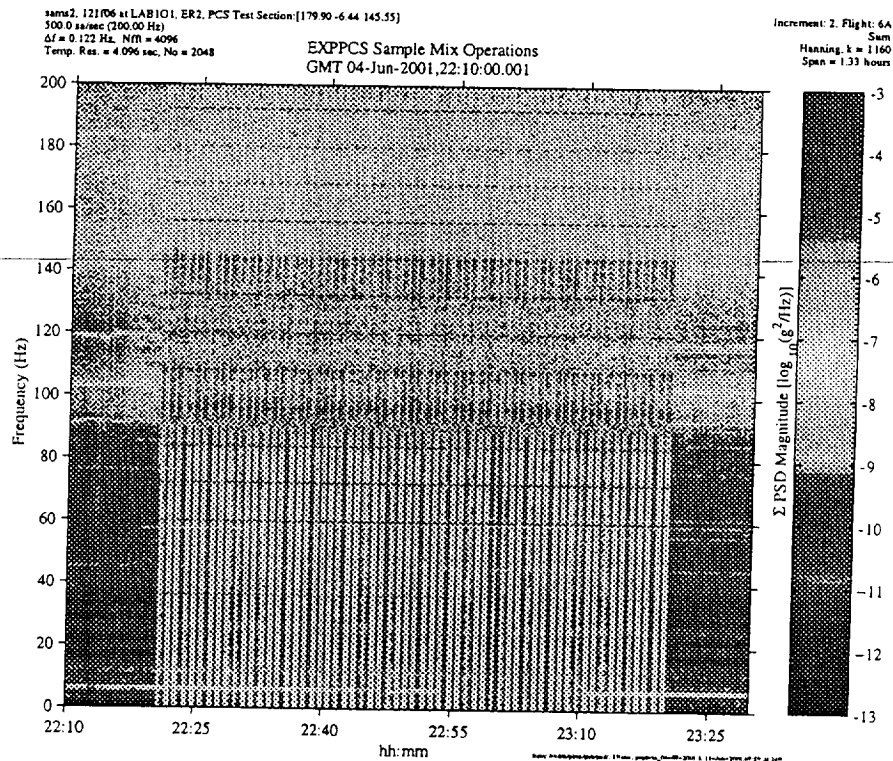


Figure 8: Physics of Colloids in Space experiment sample mixing operation

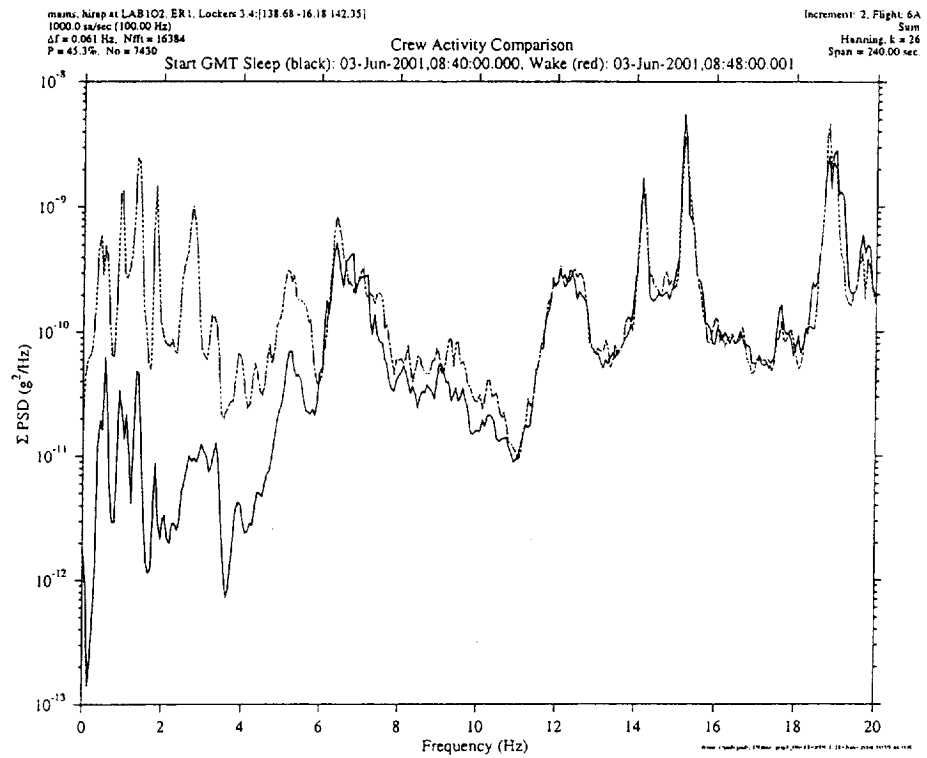


Figure 9: Comparison of crew active (upper PSD) and crew sleep (lower PSD) on International Space Station



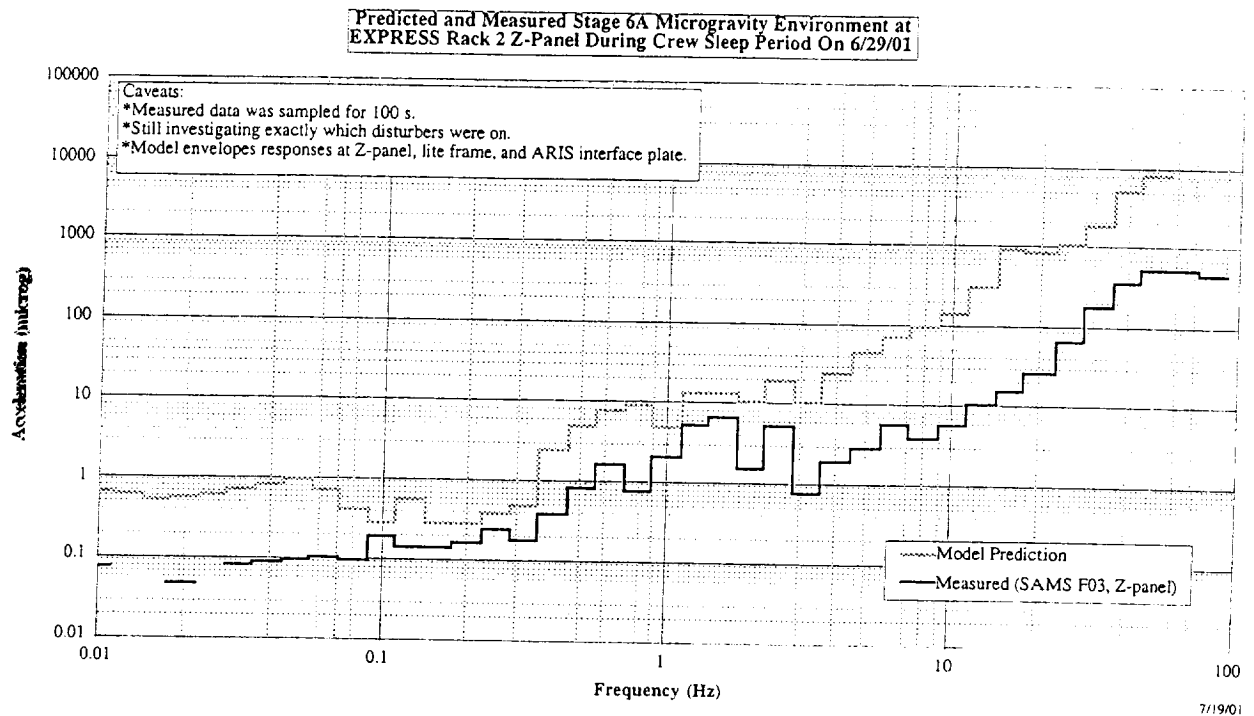


Figure 10: Predicted and Measured Stage 6A Microgravity Environment at EXPRESS Rack 2 Z-Panel During Crew Sleep Period On 29 June 2001

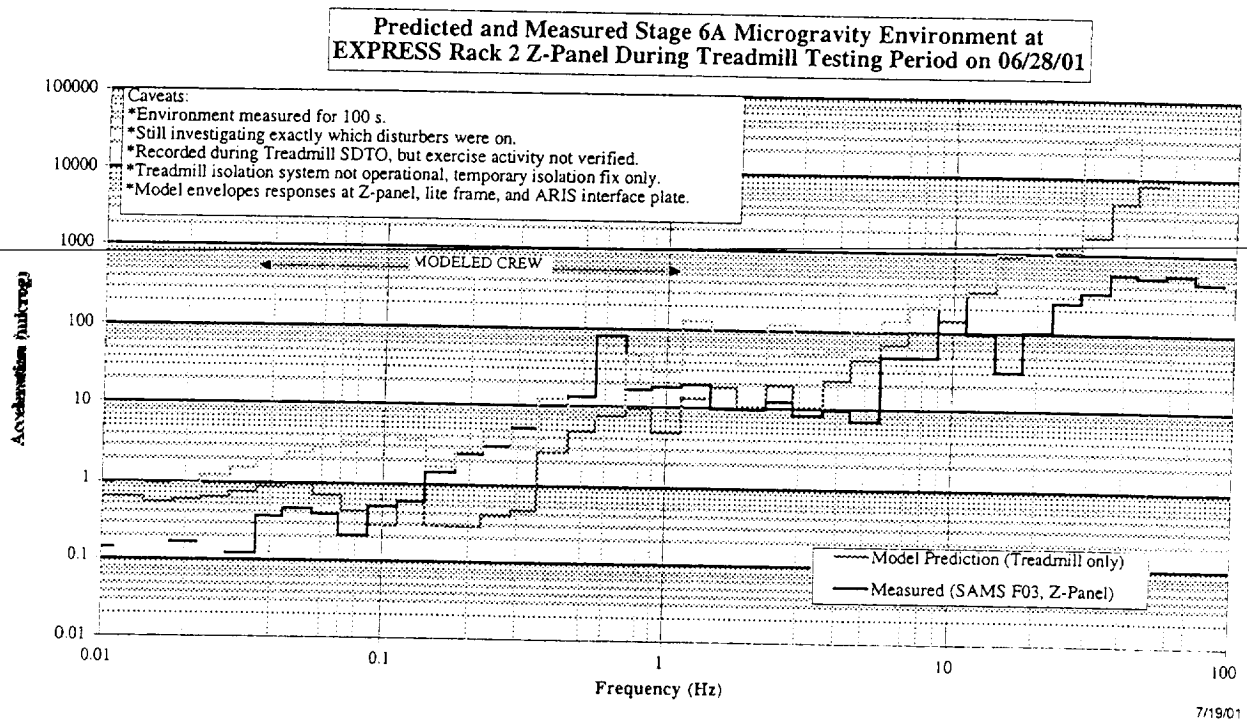


Figure 11: Predicted and Measured Stage 6A Microgravity Environment at EXPRESS Rack 2 Z-Panel During Treadmill Testing Period on 28 June 2001

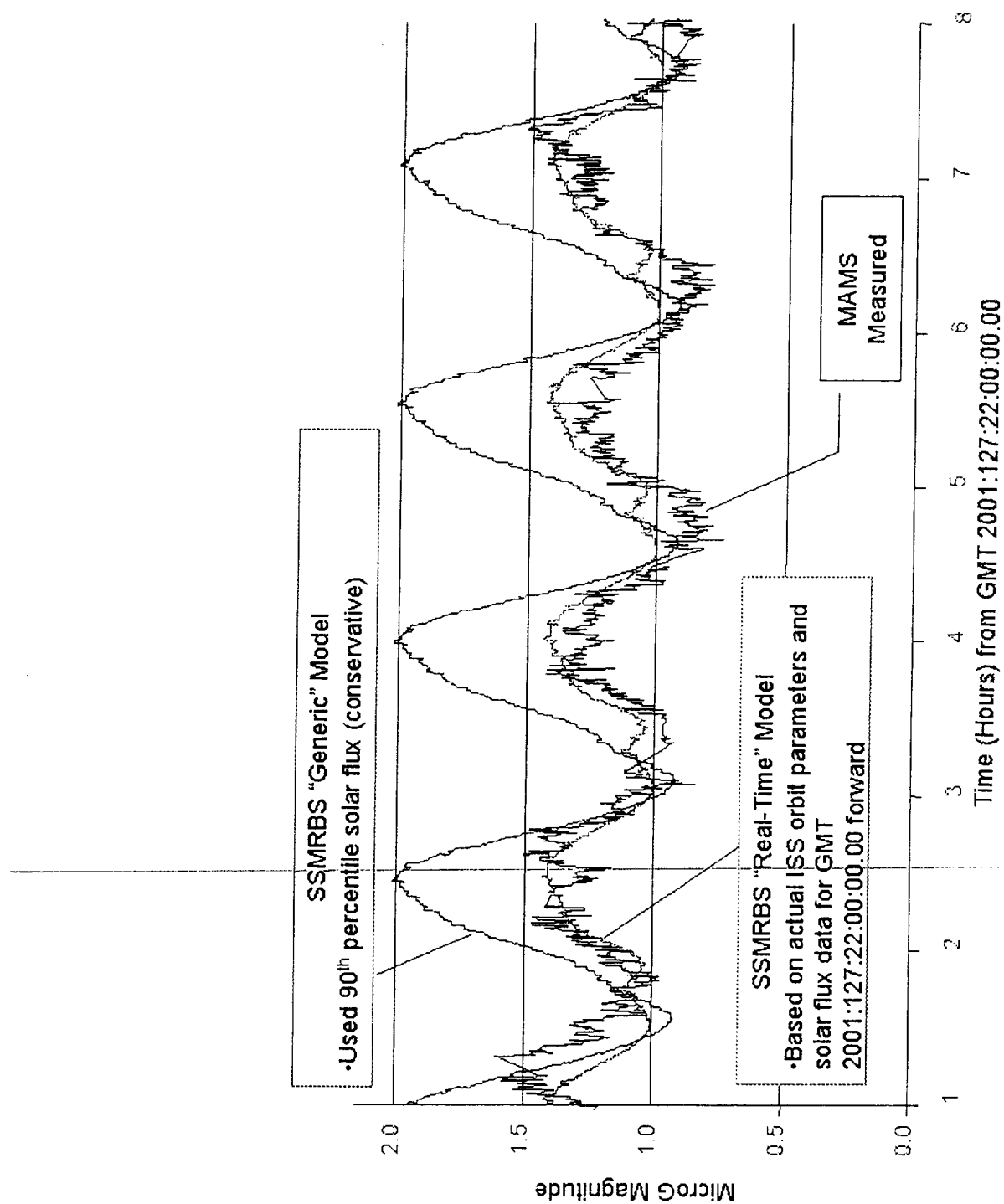


Figure 12: Measured ISS quasi-steady environment compared with analytical prediction for 6A configuration <sup>9</sup>